Unclassified

ISTEF

SPAWAR
Systems Center
San Diego

ISTEF Laser Radar Program

by

Dr. John Stryjewski
Joe Saig
Andrew Grunke
Nichols Research Corporation, KSC, FL
Brad Griffis
Computer Sciences Raytheon, KSC, FL
Michael Lovern,
SSC San Diego, San Diego, CA

CHART 1

Unclassified

Nichols

ABSTRACT

The BMDO Innovative Science and Technology Experimentation Facility (BMDO/ISTEF) laser radar program is engaged in an ongoing program to develop and demonstrate advanced laser radar concepts for Ballistic Missile Defense (BMD). Research is ongoing in both direct detection and coherent detection laser radar. The direct detection research program has been collecting metric and radiometric data on targets of BMD interest both at ISTEF and at other sites for several years. The coherent detection program is now well underway and our first data collections will occur later this year. In this talk I will discuss the research goals for both the direct detection and coherent detection programs and how they fit into the broader ISTEF laser research program. I will also present data from recent data collections to show the benefit of ISTEF advance laser radar system research to BMD in particular and BMDO in general.

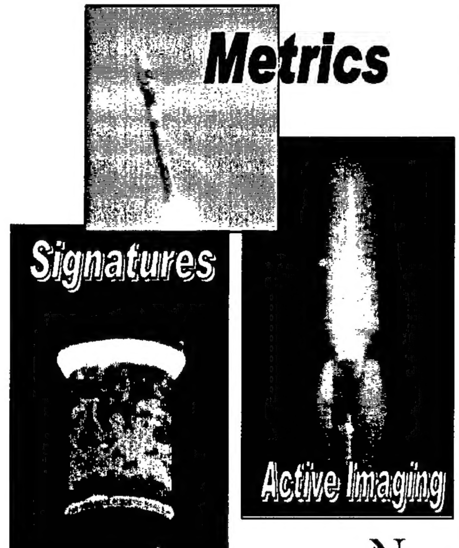
Unclassified

ISTEF

Capabilities

SPAWAR
Systems Center San Diego

- **Laboratory Testing**: ISTEF has a full range of active sensors to support component or system level laboratory testing of active and passive systems.
- **Field Testing**: ISTEF has 1 and 10 km laser test ranges and representative and surrogate BMDO targets such as: rockets, spent boosters, satellites and balloons to support field testing of electro-optic systems
- **Remote Operations**: Fully instrumented portable tracking mounts can support laser operations at the Eastern Range or any other desired location.



UCF

DITP

CHART 2

Unclassified

Nichols

The Laser Radar Program comprises one half of the laser research that is ongoing at ISTEF The other half being the Active Imaging Program. Together these to areas of research make a unified approach to studying discrimination, sensing and phenomenology issues of interest to BMDO and DOD. ISTEF's unique position as a center of excellence in active sensing allows us to pursue ideas and concepts that more specialized sensor program such as AST and SLBD can not. Having a broad charter allows us to work with other BMDO and DOD groups such as the AMSC and the USAF to solve current sensing problems while at the same time advancing concepts which are of direct applicability to advanced BMD concepts. For example, by supporting the active sensing needs of the Eastern Range during the TITAN/Cassini launch we gained valuable expertise, *and equipment*, that has greatly enhanced our ability to support the BMDO DITP program. The real-life knowledge we gain by supporting BMDO and DOD program enhances our research efforts. In turn, the our research enhances our ability to help other programs meet their data collection needs. It is this synergy between application and research that is the strength of the ISTEF laser radar program.

Unclassified

ISTEF

ISTEF Laser Radar Program

SPAWAR
Systems Center
San Diego

Direct Detection

- BMDO Application
  - Target ID
  - Kill assessment
  - Aim point selection
  - CSO discrimination
- ISTEF Innovations
  - Fiber coupled detectors
  - Dual wavelength
  - Dual mode LADAR/Imaging
  - Calibrated LRCS
  - Transportable system

Coherent Detection

- BMDO Application
  - Target ID
  - Kill assessment
  - Aim point selection
  - CSO discrimination
  - Doppler discrimination
  - Micro-Doppler discrimination
  - Cruise Missile detection
- ISTEF Innovations
  - Fiber heterodyne detectors
  - Mode-locked transmitter
  - Multi-waveform output

CHART 3

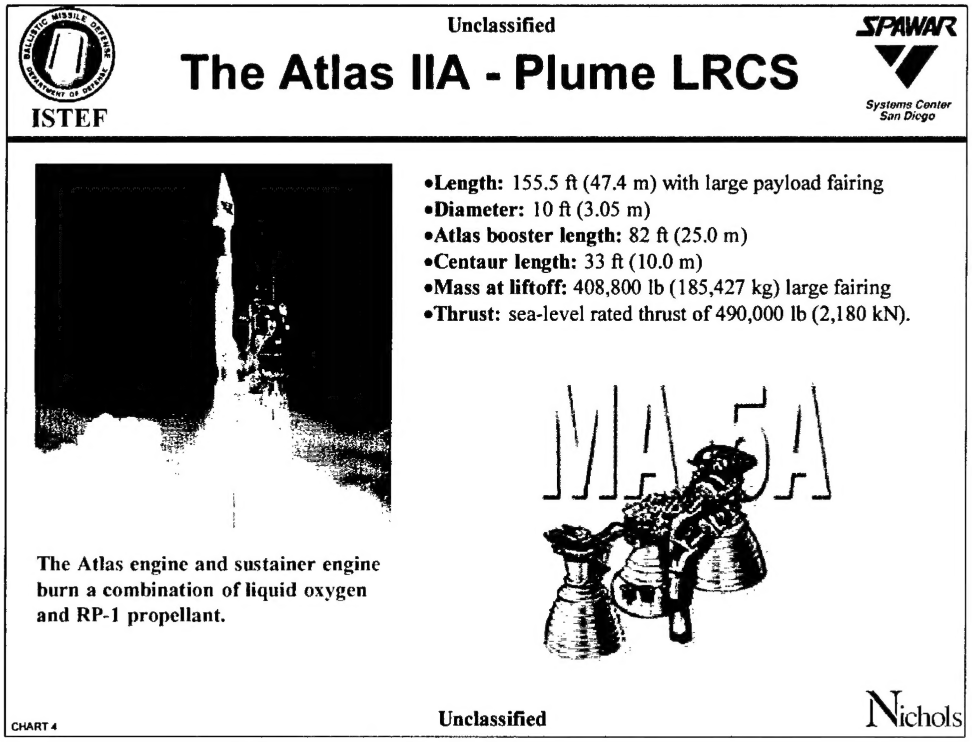
Unclassified

Nichols

The ISTEF laser radar program has ongoing research in both direct detected and coherent detected laser radar. In the past our research and BMDO support centered on the direct detection system. However, this year we made the decision to begin building a coherent detection capability. This will give us the ability to measure Doppler and micro-Doppler signatures of BMD targets.

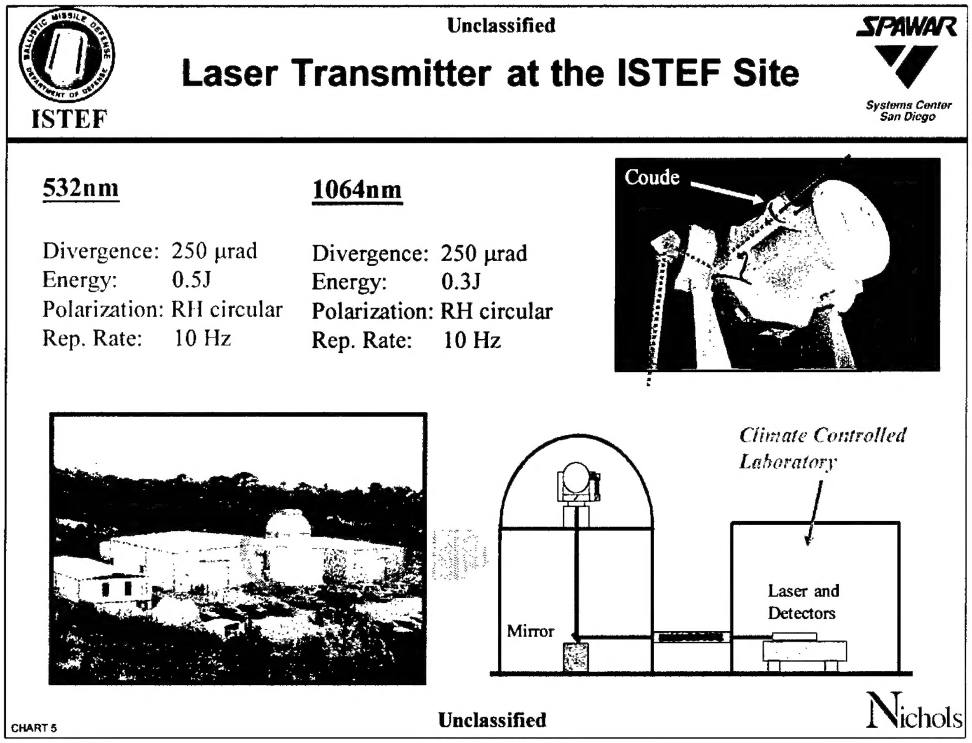
ISTEF has two direct detection LADARs. A high power pulsed system which is located at the ISTEF facility and a smaller portable system which is used for off-site data collections. Both of these systems can collect calibrated Laser Radar Cross Sections (LRCSs) at 532nm and 1064nm at ranges greater than 100km from uncooperative targets. The ISTEF direct detection systems use a robust fiber-optically coupled detector system to collect accurate data even in the harshest conditions. Additionally, these systems can also collect high resolution laser range-gated images at 532nm.

The new coherent detection system operates at 1064nm and will provide high resolution range-Doppler and range-micro-Doppler images of BMD targets. As described later in this talk this system uses a novel mode-locked waveform to increase the combined range-Doppler resolution. Additionally, this development path will lead to a transportable coherent LADAR to support BMDO testing.



From a signature and a phenomenology perspective the laser radar cross section (LRCS) of LOX-hydrocarbon plumes are of great interest to the BMDO community. In particular, understanding the concentration of soot in these plumes is critical to understanding their signatures. Current plume models can not accurately predict the concentration and distribution of this soot within the plume. Laser illumination is an ideal tool to study the soot concentration in plumes because the only contributor to the LRCS is soot. Unlike passive sensors, the laser is essentially blind to the hot gasses in the plume. When the LRCS data is combined with passive IR data a much more complete picture of the plume is possible.

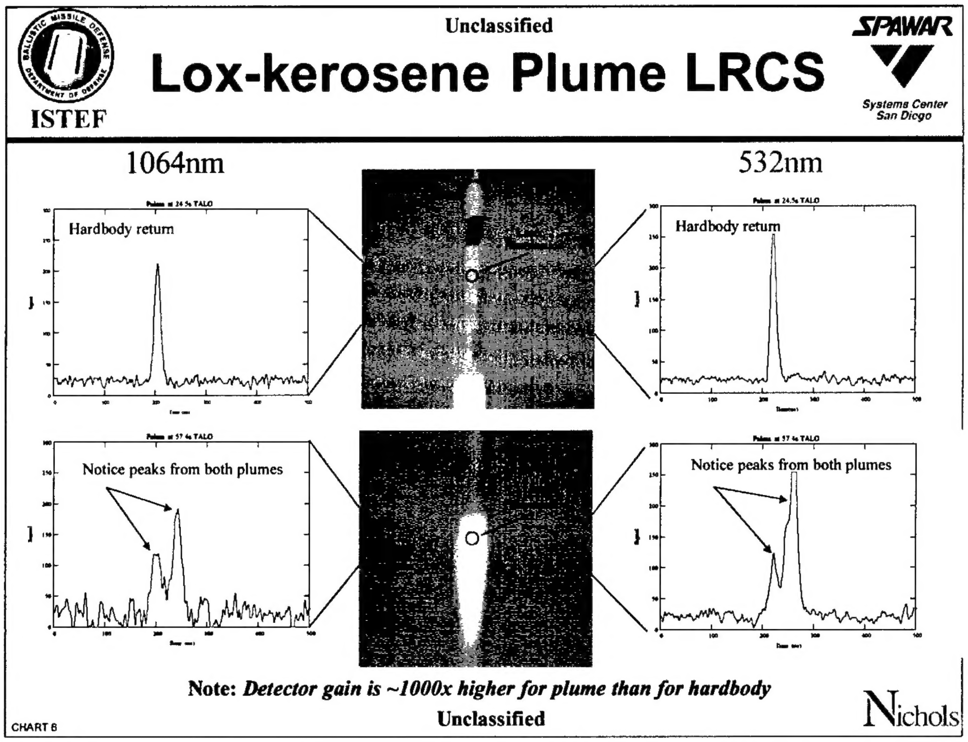
The Atlas rocket is an excellent surrogate for actual BMD threats because the first stage uses a LOX-kerosene propellant. The ISTEF site, being located at Cape Canaveral Florida, has the opportunity to observe a number of these rockets each year. On March 16, 1998 we observed and laser illuminated the hardbody and plume of Atlas AC-132 (ER op number A7050). Calibrated LRCSs for the LOX-kerosene plume were measured simultaneously at two wavelength (532nm and 1064nm). The following slides describe these results.



The plume soot data were collected using the ISTEF transmitter site. This transmitter uses a frequency doubled Nd:YAG illuminator operating at both 1064nm and 532nm. The transmitter is located in a laboratory building adjacent to the transmitter dome. The beam is directed via a mirror path to the dome and exits a 2in-aperture coude path. The coude path is co-located with a 20in aperture Cassegrain receiver telescope. The received light is launched into an optical fiber and transmitted to the laboratory building where the detectors reside. The detectors for this experiment were high gain avalanche photodiodes (APDs). This setup has the advantage that both the transmitter and detector are in a climate controlled laboratory, only the telescope optics are subjected to the outside environment.

The output energy, divergence and polarization are controlled independently for each wavelength. This allows us to insure that the illumination functions of the two wavelengths are identical at the target. The range to the target for this experiment varied from 10km at launch to about 60km when we stopped illuminating.

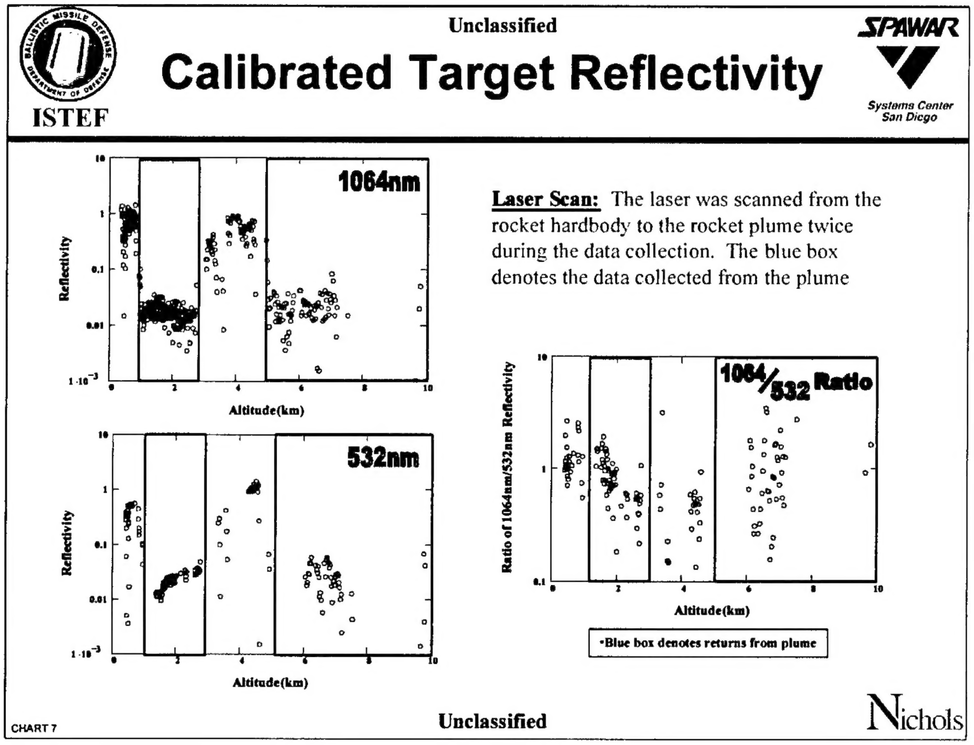
The measured LRCSs were absolutely calibrated using a combination of laboratory and field measurements.



This slide shows examples of raw data collected from the rocket and plume. The graphs show the raw output of the high speed digitizer that recorded the APD signals. The full horizontal scale (500ns) corresponds to 250ft (76m). The upper graphs show the hardbody returns in the visible and infrared. The lower graphs show the returns from the soot in the plume.

One can clearly see the excellent signal-to-noise and the high spatial resolution of the data. The Atlas rocket has two main engines on the first stage (see slide 4). On the images above one engine is behind the other. In the two lower graphs, the soot signatures of the two plumes are clearly resolved by the laser. The Atlas has a third, sustainer, engine on the first stage but the thrust (soot output) is too low to be visible in the data.

Also, note that the detector gain for the plume measurements (lower graphs) was 1000 times higher than for hardbody measurements (upper graphs). The background noise in the plume graphs is due to the broadband luminance passing through our narrow band-pass filters (3nm band pass). Lastly, note that the small circle on the images illustrates the beam illumination spot on the target.

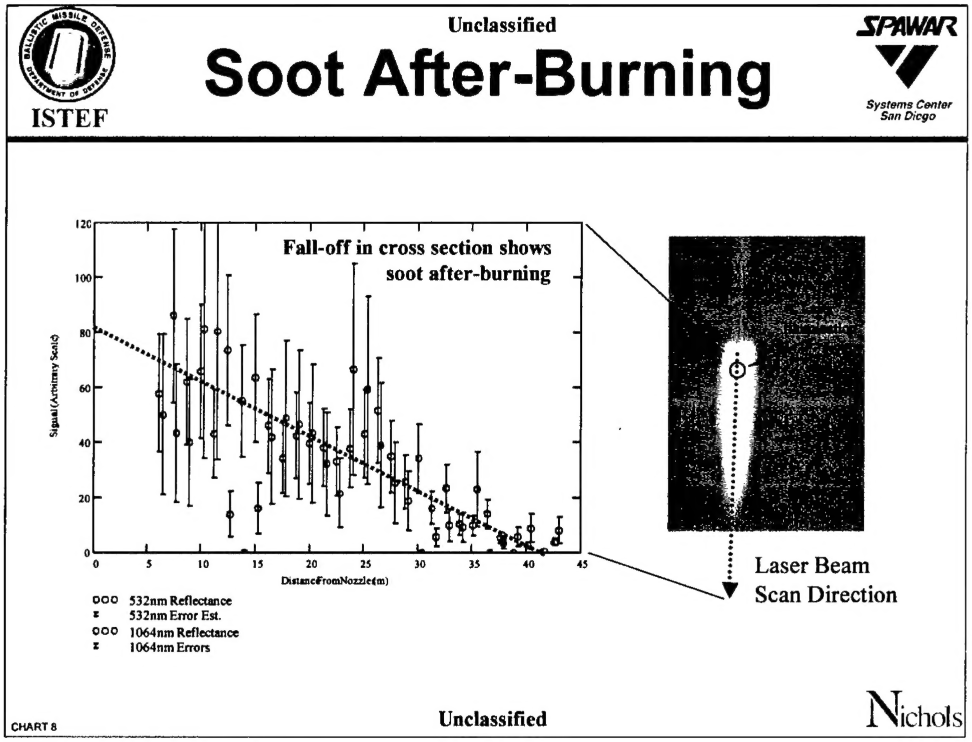


This slide shows the ***calibrated*** data from the rocket hardbody and plume. For ease of comparison data is expressed in units of reflectance. This was calculated by taking the ratio of light reflected by the target to the light incident on the target. For the plume, the returns were integrated in the beam direction, yielding an effective reflectivity.

During data collection, the laser beam was scanned from the hardbody to the plume, back to the hardbody and then back to the plume. Scanning onto the hardbody aided in verifying the accuracy of the atmospheric extinction model. The data which is outlined by blue boxes is the plume data, the remainder is hardbody data. During the plume measurements, the laser beam was designated to a point about 5-10m below the nozzle exit plane.

The two graphs at the left show the the calibrated target reflectivities at 532nm and 1064nm. Note: the vertical scale is logarithmic. The very low reflectivity (remember: soot is black) of the soot is apparent in at both wavelengths.

The third graph shows the ratio of the 1064nm to the 532nm reflectivity. From this graph we can see that the plume reflectivity ratios are similar to the hardbody ratios. This implies that the scatterers (soot particles) are on the order of 1 micron or larger.



During an earlier mission, we examined the dependence of the soot cross section on distance from the engine nozzle exit plane. The target on this mission was also an Atlas rocket launched from Cape Canaveral. The laser transmitter and receiver were virtually identical to those used to collect the data shown on the previous sides.

The graph at the left shows the resulting plume reflectivity when the laser beam is scanned from 0 to 45m below the nozzle exit plane. The vertical scale is not absolutely calibrated. However, it is very clear that the soot cross section (reflectivity) falls off dramatically with distance from the exit plane.

This fall-off dramatically shows the effects of soot after-burning. Soot after-burning occurs when soot produced in the fuel-rich combustion chamber mixes with the atmospheric oxygen and burns. As the soot is after-burned, the LRCS decreases, as is clearly seen at both wavelengths.

Understanding soot after-burning is critical to generating reliable plume signature codes. This is especially important since, at some altitude the partial pressure of oxygen will decrease to a point where after-burning will cease. Predicting this transition is an particularly important when predicting boost phase intercept signatures.

ISTEF

Coherent LADAR

SPAWAR Systems Center San Diego

In coherent detection the signal electric field, $E_{received}$ is mixed with a CW local oscillator. The combined signal has both direct detected and a coherent (heterodyne) contributions. The heterodyne term contains all of the Doppler information.

$$Signal_{heterodyne} = (E_{local\ oscillator} + E_{received})^2$$

$$= \underbrace{E_{received}^2}_{\text{Direct Detected Signal}} + \underbrace{E_{local\ oscillator}^2}_{\text{Zero for CW local oscillator}} + \underbrace{E_{received} * E_{local\ oscillator}}_{\text{This term contains the Doppler information}}$$

<u>Benefits of Coherent Detection:</u>

- •Doppler Information
- •Higher Sensitivity
- •Better Noise Rejection
- •More Amplitude Bandwidth

<u>Pulsed Coherent LADAR trade-off:</u> ⇨
long pulse = good Doppler resolution and bad range resolution
short pulse = bad Doppler resolution and good range resolution

CHART 9

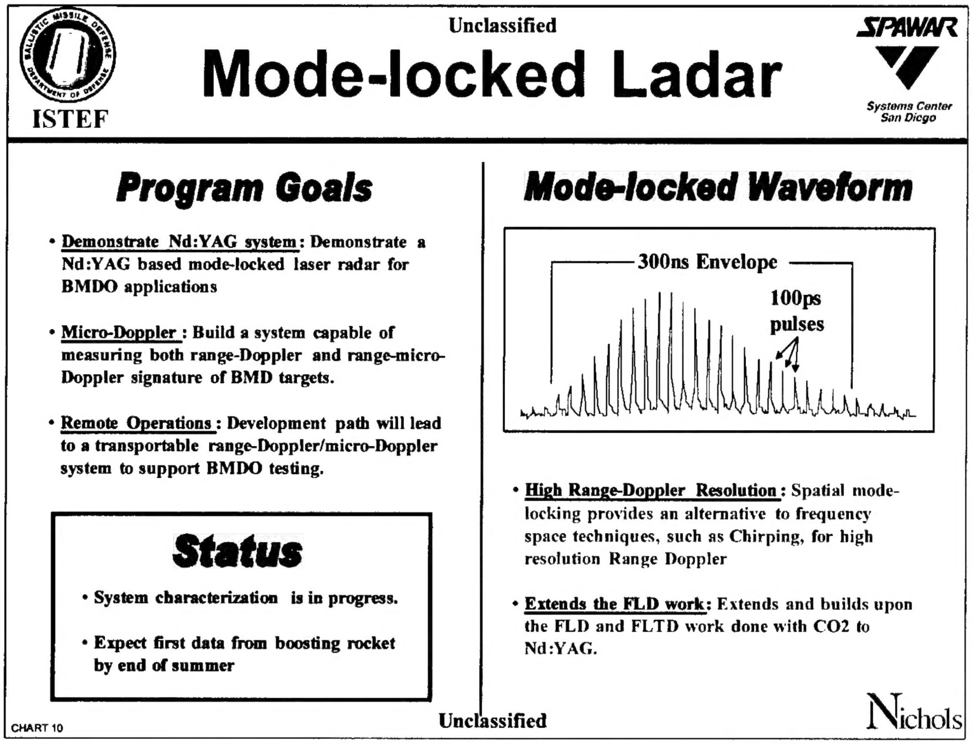
Unclassified

Nichols

In the previous slides I presented data that ISTEF collected using direct detection LADAR. For the remainder of this presentation I will concentrate on the ISTEF ***coherent detection*** laser radar program.

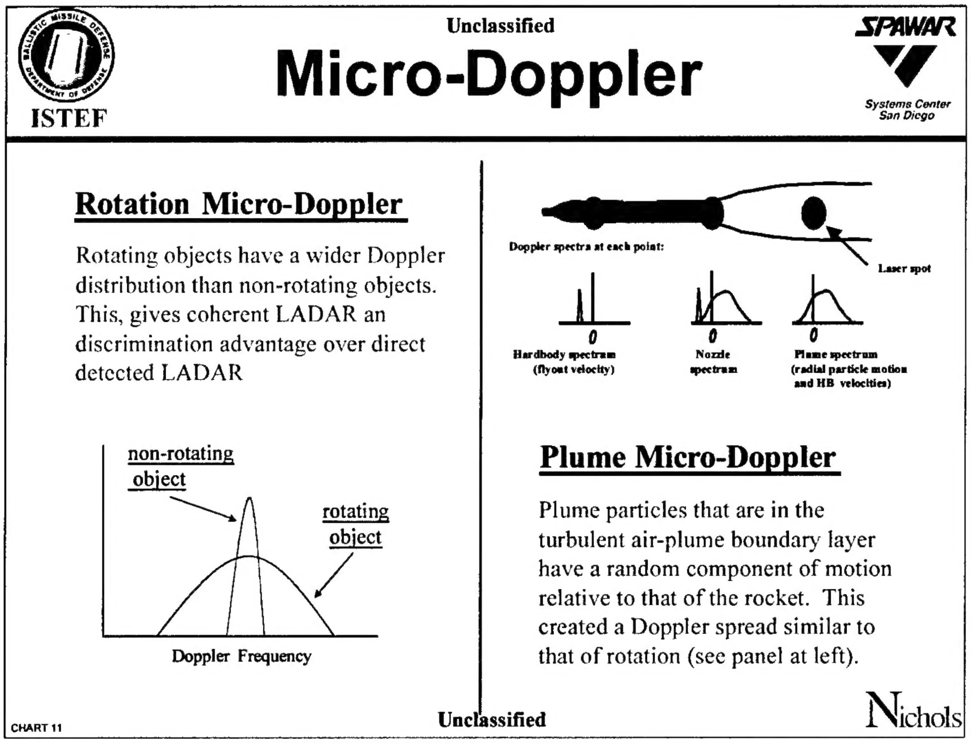
A coherent detection laser radar differs from a direct detection laser radar in two respects. First, the transmitter must emit a true single frequency (narrow frequency bandwidth) to be efficient. This means that a laser must be have a more sophisticated design when used with a coherent laser radar. Second, and more importantly, the the detection scheme is different in a coherent LADAR. In coherent detection the received signal is mixed with a separate "local oscillator" laser source and the resultant combined signal is then detected in the usual way. In addition to the the familiar direct detection signal (see above), this scheme generates a signal (cross term) that is proportional to the product of the return-signal electric field and the local-oscillator electric field. This cross term contains information about the motion of the target due to the Doppler shift of the light returned from the target. Coherent detection has a number of advantages over direct detection including, Doppler information, higher sensitivity and better noise rejection.

However, there is one import trade-off when designing a system to measure both range and Doppler. This is the tradeoff between pulse width and Doppler resolution.



For a single coherent pulse, the frequency bandwidth is inversely proportional to the pulse width. Thus, for high range resolution, one would want a short pulse. However, this would give poor velocity (Doppler) resolution. The standard solution to this problem is the use a long pulse (good Doppler resolution) that is modulated to improve the range resolution. The most common method is to introduce a frequency modulation, or "chirp", when the pulse in emitted. Another less common method to improve the range resolution is to spatially modulate the pulse. The ISTEF LADAR uses a type of spatial modulation known as spatial mode-locking. A "mode-locked" laser produces a waveform like the one shown above. The generated waveform is a 300ns train of 100ps pulses spaced 10ns apart.

Our goal for this system is to demonstrate a Nd:YAG based, mode-locked, laser radar for BMDO applications. The system will be capable of measuring both range-Doppler and range-micro-Doppler (see next slide) signatures of BMD targets and has a development path leading to a transportable range-Doppler/micro-Doppler system to support BMDO testing. Currently, we are in the final stages of system testing and configuration and we expect to collect Doppler data from a boosting rocket by end of summer.



In addition to measuring the target velocity component relative to the transmitter (Doppler signature) we intend to measure the "micro-Doppler" signatures of BMD targets. Micro-Doppler signatures arise from internal vibrations, rotation or deformations of the target. The ISTEF LADAR effort will concentrate on rotation micro-Doppler and plume micro-Doppler (see above).

Rotation micro-Doppler arises because rotating objects have a wider Doppler distribution than non-rotating objects (see above). Plume micro-Doppler arises because plume particles that are in the turbulent air-plume boundary layer have a random component of motion relative to that of the rocket. The effect of this is to generate a Doppler spread similar to that of a rotating object (see above).

The added signature information provided by a micro-Doppler sensing LADAR can aid in target discrimination and target identification. The added discrimination capability can be especially useful for separating CSOs and for defeating both unintentional and intentional BMD countermeasures.

ISTEF

Unclassified

Summary

SPAWAR
Systems Center San Diego

- The ISTEF LADAR program combines research into new detection methods with BMDO relevant field collections to enhance both BMDO's tests and ISTEF's research.
- ISTEF has a demonstrated the capability to measure calibrated LRCS of the soot plume from a threat surrogate target. This data is of utility to plume phenomenologists and signature modelers
- ISTEF is currently extending it's capabilities to include a coherent LADAR (using heterodyne detection). Using a mode-locked laser transmitter we will demonstrate the utility Doppler and micro-Doppler signatures for BMD discrimination and identification

CHART 12

Unclassified

Nichols

The ISTEF LADAR program combines research into new detection methods with BMDO relevant field collections to enhance both BMDO's tests and ISTEF's research. We have used our direct detection capability to measure calibrated LRCS of the soot plume from a threat surrogate target. This data is of great utility to signature modelers and plume phenomenologists. We are currently extending ISTEF's capabilities to include a coherent LADAR (heterodyne detection). Using a mode-locked laser transmitter we will demonstrate the utility Doppler and micro-Doppler signatures as BMD discriminants.

Our continuing research into laser radar methods and our ongoing support of BMDO and DOD programs go hand-in-hand. The synergy between application and research enhances our ability to support BMDO research and testing with active sensors.

This work was performed under BMDO contract N66001-95-D-0088.

The Authors would like to thank the following people for their contributions during the collection and analysis of data presented in the talk: Rolf Ahlgreen, Michael Hill, Bruce Eskamani, and Debbra Gentry